Development of resilient and environmentally responsible highway infrastructure solutions using geopolymer cement concrete

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ABSTRACT: Despite local and national road authorities striving to provide motorists with a durable and safe infrastructure environment, one in six UK roads is currently classed as being in poor condition. In terms of safety, Department for Transport statistics continue to report high numbers of road fatalities; 1,780 in 2015, representing a 3% increase from the previous year. As such, research focussed on developing resilient and cost effective planned/preventative highway maintenance solutions remains highly topical. Reported in this paper is research aimed at developing high performance, low impact solutions for both highway repair and skid resistance enhancement. Based on a metakaolin/alkali silicate-based geopolymer cementitious material, a mix optimisation investigation is initially reported, providing key fresh and mechanical material properties such as setting time and compressive/flexural strength. Using optimum mix designs, the paper then presents an assessment of geopolymer cement concrete's suitability as a highway repair material. To this end, wear and skidding resistance characteristics of potholes repaired with geopolymer cement concrete is reported, with initial findings suggesting excellent performance levels. Finally, the paper examines the potential use of a geopolymer cement-based artificial aggregate as a cost effective alternative to calcined bauxite for high friction surfacing applications. Initial production trials of aggregate will be discussed, together with effects of accelerated trafficking on texture depth retention.

KEY WORDS: Geopolymer Cement; Novel Cements; Road Maintenance; Permanent Road Repair; High Friction Surfacing.

1 INTRODUCTION

Interest from the construction industry in sustainable alternatives to conventional Portland cement has grown in recent years. Geopolymer cement provides an attractive alternative, due to advantageous performance and environmental properties. It is claimed that geopolymer cement production can achieve up to 90% less CO_2 emissions when compared with Portland cement production [1, 2]. Mechanical properties such as high compressive and flexural strengths [3], acid and sulphate resistance [4] and freeze-thaw resistance [5] make geopolymer cement suitable for a wide range of potential applications. Despite the impressive mechanical properties, a lack of harmonised standards in the UK and Europe have created a barrier to the use of geopolymer cement, and other alkali-activated cementitious materials (AACM). However, a Publicly Available Specification (PAS) considering AACMs is to be released in 2016 [6]. This document will set performance based requirements for AACMs where an aluminosilicate material and an alkali activator are used to form a cementitious binder. While some researchers argue that AACMs and geopolymer cements are different materials, this PAS will include cementitious binder systems which are marketed as geopolymer cements.

Road pavement applications have been identified as potential areas which could take advantage of the impressive performance properties of geopolymer cement. Firstly, potholes are a common issue across the entire UK road network, with one in six roads regarded as being of a poor standard [7]. In excess of 2.5 million potholes were repaired in England and Wales in 2014, at an average cost of £57 per pothole. Despite this significant cost, an estimated £12 billion is required to bring the UK road network back to a good standard. Geopolymer cement may provide a solution to this issue. Limited research has been carried out in this area, with a Thai study reporting the suitability of geopolymer cement, albeit based on compressive and bond strength, rather than durability testing [8].

A second potential use for geopolymer cement is as a high performance aggregate, used as an alternative to calcined bauxite in high friction surfacing systems. High friction surfaces play an important role in the reduction of road traffic collisions, reducing injuries and saving lives. In service studies have shown a reduction in collisions by more than 50% after the application of a high friction surface [9]. These systems use calcined bauxite, a highly durable and hard-wearing aggregate, to provide additional grip to an existing road surface. The aggregate is bonded to the surface using an epoxy resin. While high friction surfacing is proven to reduce injuries and deaths on public highways, when correctly placed, the cost and environmental impact of the calcined bauxite have meant that alternative materials are required. While bauxite is a locally available aggregate in Northern Ireland, material suitable for high friction surfacing applications can only be sourced from countries such as China and Guyana, due to differences in the chemical structures of the aggregates. Long transportation distances, combined with quarrying, crushing, grading and high temperature calcination mean that the environmental impact of calcined bauxite is significant. When the cost of these processes, in addition to the environmental impact of the material, are considered, a suitable alternative would have a major impact on the high friction surfacing market.

This paper reports preliminary findings from a research programme focusing on the development of a geopolymer mortar mix design, the selection of a suitable mortar for use as a geopolymer pothole repair material, and a geopolymer aggregate formed from waste geopolymer mortar for use in a high friction surfacing system.

2 EXPERIMENTAL PROGRAMME

2.1 Materials

This study focuses on the application of a calcined clay-based geopolymer cement system. Kaolinitic clays, an exposed layer at existing basalt quarries in Northern Ireland, have been identified as suitable aluminosilicate materials for geopolymerisation. The clay is calcined at 750ºC, then ground to a fine powder. When mixed with a potassium silicate solution (approximately 55-60 wt. % potassium solids), geopolymerisation occurs, forming a cementitious binder similar to that of an ordinary Portland cement and water binder. This system, BanahCEM, is commercially produced in Northern Ireland and was used throughout the study. Aggregate for the mortar was locally sourced concreting sand. Mortar was mixed using a table top mixer. The mixing process was carried out in accordance with supplier instructions due to the lack of harmonised standards regarding the mixing of geopolymeric materials.

2.2 Mixture Proportions

Three variables which can impact upon the mechanical properties of geopolymer mortar are metakaolin powder content, activator content, and water content. For this study, content ranges were set for each variable. Three points within these ranges were selected, giving an upper, middle and lower content levels. For each mix, the content level of one variable was changed, with the two other variables remaining at the middle content level, as shown in Table 1. In order to maintain a constant mix density of 2400 kg/m^3 for each mix, the sand content was adjusted depending on the other variable contents.

Table 1. Mix proportions for geopolymer mortar strength testing.

Mix	Mix Proportions (kg/m^3)				Geopolymer Liquid/Solid ratio
	Banah CEM Powder	Banah CEM Activator	Sand	Water	
1	500	300	1545	55	0.264
2	500	350	1495	55	0.282
3	500	400	1445	55	0.299
4	450	350	1545	55	0.304
5	500	350	1495	55	0.282
6	550	350	1445	55	0.264
7	500	350	1500	50	0.275
8	500	350	1495	55	0.282
9	500	350	1490	60	0.289

2.3 Compressive and Flexural Strength

Compressive strength testing was carried out on geopolymer mortar cubes, measuring 50 x 50 x 50 mm. Flexural strength was tested on geopolymer mortar beams measuring 40 x 40 x 160 mm. Specimens were cast in steel moulds and wrapped with polythene sheet to retain moisture during the initial hardening and curing phase. After 24 hours, the specimens were demoulded and stored at an ambient temperature of 20 ± 2°C, until testing was carried out. Compressive and flexural strengths were determined according to BS EN 1015-11: 1999 [10].

2.4 Geopolymer Mortar Workability

The workability of a pothole repair material is an important factor when determining the suitability of a material for use as rapid and permanent road repair material. Two workability tests were carried out. Mortar flow was measured using a table top flow table, in accordance with BS EN 1015-3: 1999 [11]. Mortar setting time was measured using manual vicat apparatus, according to BS EN 196-3: 2005 [12]. The workability tests were carried out on the mix which was selected, based on the compressive and flexural strength results.

2.5 Pothole Repair Material

An asphalt slab, with dimensions of 275 x 275 x 40 mm, was produced. Using a hammer and chisel, material was manually removed to form a circular defect with irregular sloped sides, and an approximate volume of 0.001m^3 (Figure 1). The irregular shape of the defect meant that the conditions in which the geopolymer mortar would have to bond to the asphalt were poor, meaning that there was a risk of the mortar popping out of the specimen. This provided a worst case scenario for which the geopolymer mortar may have to endure. The high strength geopolymer mortar was placed in the defect and compacted using a steel tamping rod, followed by 30 seconds on a compacting table. An excess of the material was removed using a hand trowel. No additional surface texturing was applied to the geopolymer mortar. The slab was wrapped in a polythene bag for 24 hours for moisture retention. After 24 hours, the polythene was removed, and the slab was stored at an ambient temperature of 20 ± 2 ºC for 6 days prior to testing.

Figure 1. A simulated pothole for geopolymer repair material investigation.

2.6 High Friction Aggregate

The geopolymer high friction aggregate was produced using waste geopolymer mortar specimens from the initial geopolymer strength testing studies. After the specimens were tested for compressive and flexural strength, the mortar was crushed using a jaw crusher. This formed a recycled geopolymer mortar aggregate. The material was sieved, according to BS EN 1015-1: 1999 [13] to retain particles sized from 1 to 3 mm. A 1:1 ratio of two part epoxy resin was mixed, and a 2 mm layer applied to a 10mm stone mastic asphalt (SMA) slab with dimensions of 300 x 300 x 50 mm. The geopolymer aggregate was dispersed over the slab until the epoxy had been covered. After allowing the epoxy resin to cure for 24 hours, excess aggregate was removed using a wire brush. Figure 2 shows the geopolymer high friction surface slab, prior to testing. This production method was then repeated with a second 10 mm SMA slab, using conventional calcined bauxite aggregate with the epoxy resin binder. This slab was tested alongside the geopolymer slab as a control sample to provide a benchmark for the initial geopolymer aggregate investigation.

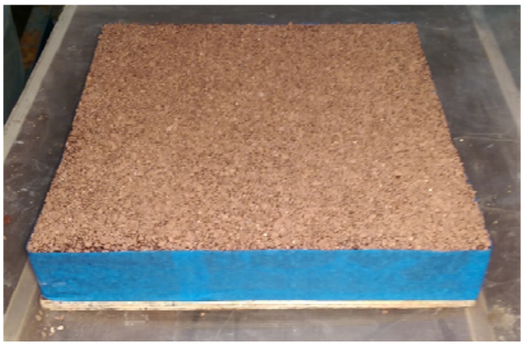

Figure 2. Crushed geopolymer mortar high friction surface test specimen.

2.7 Simulated Wearing and Skid Resistance

Accelerated wearing was carried out according to Appendix H of TRL Report 176 [14], using the Ulster University road test machine. The machine configuration involves loading 2 pneumatic tyres to 5 ± 0.2 kN. The tyres pass over the specimens at a rate of 10 revolutions per minute, and are free to move 160±25 mm laterally across the specimens. This machine replicates low speed and high friction traffic loading, the harshest form of loading which a road surface can be subjected to. The pothole sample was subjected to 2000 wheel passes. The high friction surface slabs were subjected to 20,000 wheel passes.

As no surface texture was applied to the pothole sample, surface wearing was identified by a visual assessment. The surface texture changes of the high friction surfaces were quantified using the sand patch test method. This method measures the road surface macrotexture. The test, according to TRL Report 176 Appendix D [14], involved spreading a known quantity of silica sand in an even circle over the surface of the specimen. The diameter of the circle is measured and the textured depth is calculated using the equation:

$$\text{Texture Depth} = \frac{[illegible]}{[illegible]} \text{ mm}$$

Skid resistance was measured according to RRL Road Note 27 [15]. The samples are saturated with water and pendulum apparatus is used to measure the resistance between the surface and a rubber slider which is attached to the pendulum. Skid resistance is measured in wet conditions, as a wet surface provides the lowest skid resistance value.

3 RESULTS AND DISCUSSION

3.1 Compressive and Flexural Strength

Table 2 shows the mean 7 day compressive strengths, and mean 28 day compressive and flexural strengths. As shown in the results, all specimens exhibited 7 day compressive strengths of at least 89% of the 28 day compressive strengths. Mixes 4 and 9 achieved the 28 day strength after 7 days, while mix 3 showed a slight reduction in compressive strength of around 3%, between 7 days and 28 days. As mix 3 had a higher activator content than the other mixes, this may suggest that the activator content exceeded the maximum content level of this component. Figure 3 illustrates the relationship between 7 day and 28 day compressive strengths. It was also found that the majority of 28 day flexural strength results were around 4% of the corresponding 28 day compressive strengths. This is a common trend when testing mortars using only fine aggregate. However, no trend between 28 day compressive strength and 28 day flexural strength was obvious from this investigation.

Table 2. Geopolymer mortar compressive and flexural strength results.

Mix no.	Compressive strength (N/mm^2)		Flexural strength (N/mm^2)
	7-day	28-day	28-day
1	59	62	2.7
2	66	67	2.4
3	61	59	2.7
4	54	54	2.7
5	66	67	1.7
6	69	77	2.3
7	69	76	3.1
8	66	67	2.7
9	58	58	2.4

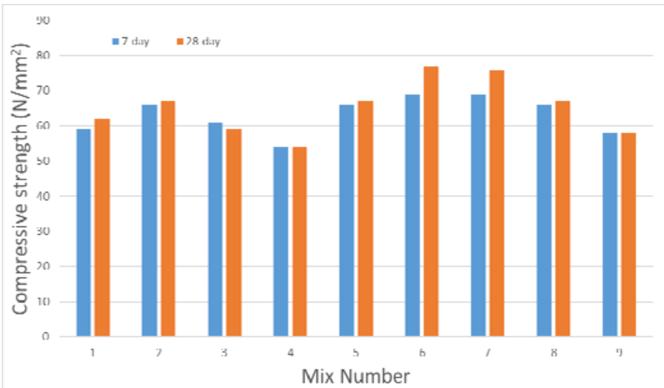

Figure 3. Relationship between 7 day and 28 day compressive strengths of geopolymer mortar mixes.

The ratio of geopolymer binder liquids to geopolymer binder solids is thought to play a role in the compressive strength of geopolymer mortar, much like the effect of water/cement ratio when using ordinary Portland cement. Figures 4 and 5 show the effect of geopolymer liquids to solids, for 7 day and 28 day compressive strengths respectively. As shown in figure 4, after 7 days, the general trend is that compressive strength decreases, as the geopolymer liquids to solids ratio increases (R^2=0.35). Figure 5 shows that this relationship becomes more apparent for 28 day compressive strength (R^2=0.54).

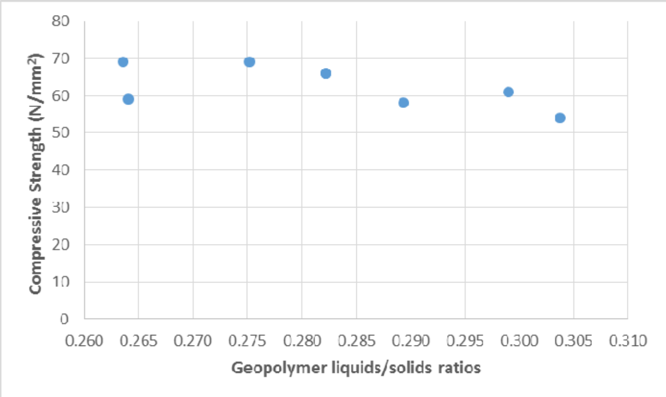

Figure 4. Effect of geopolymer liquids to geopolymer solids ratio on the 7 day compressive strength of geopolymer mortar.

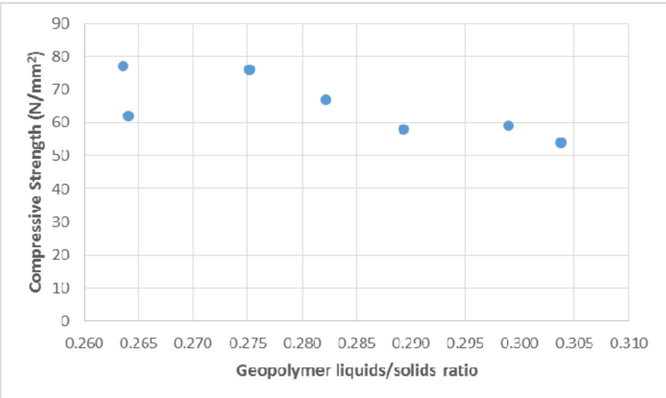

Figure 5. Effect of geopolymer liquids to geopolymer solids ratio on the 28 day compressive strength of geopolymer mortar.

The ratio of activator to powder also appears to play some role in the 28 day compressive strength of geopolymer mortar. This trend is shown in Figure 6, where R^2=0.25. However, some variance in the results would indicate that the geopolymer liquid to solids ratio plays a more important role in the geopolymer strength development.

The Specification for Highway Works Clause 1001 states that concrete for use as a surfacing material must be classed as CC37 [16]. This means that 7 day and 28 day compressive strengths of 32 N/mm^2 and 37 N/mm^2, respectively, are required for use as a surfacing material. This means that all mixes have exceeded the minimum compressive strength requirements. In addition, it has been proposed that a minimum 2 hour flexural strength of 2.4 N/mm^2 is required when testing repair materials under laboratory conditions [17]. While seven of the mixes achieved this strength at 28 days, further testing will be required to determine the 2 hour flexural strength.

Mix 7 was selected for further workability testing, and for testing as a pothole repair material. This selection was based on the mix providing the highest flexural strength, along with high 7 day and 28 day compressive strengths.

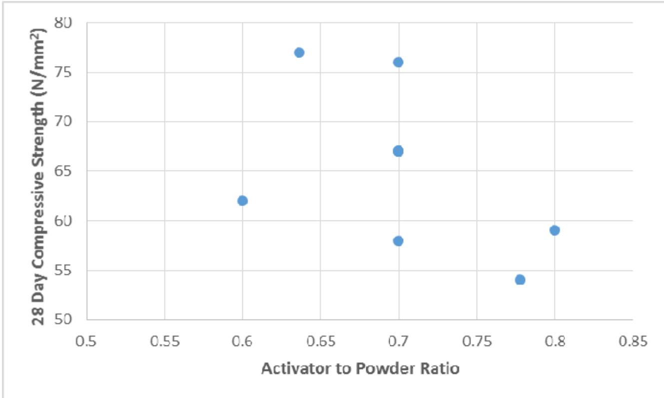

Figure 6. Effect of activator to powder ratio on 28 day compressive strength of geopolymer mortar.

3.2 *Fresh pothole repair properties*

The flow of the geopolymer mortar was recorded as 193 mm. According to BS EN 1015-6: 1991, this mortar can be classed as a plastic mortar, as it falls within the plastic mortar flow range of 140 to 200 mm [18]. The initial and final setting times were recorded as 150 minutes and 180 minutes, respectively.

The flow result of the mortar indicates a suitable level of workability for use as a repair material. The material is likely to require little compaction, and will be easy to spread into all areas of the defect to maximize bond adhesion. However, according to the Specification for Highway Works clause 946 [19], a pothole repair material should have cured sufficiently to withstand heavy vehicle trafficking after 30 minutes. With a final setting time of 180 minutes, the geopolymer mortar would require the setting times to be significantly reduced to be of use as a pothole repair material.

3.3 *Pothole Repair Performance*

After 20,000 wheel-passes, a visual assessment of the specimen was carried out. As geopolymer mortar is an untested material in this application, using this test method, it was expected that some performance issues would occur during the initial testing. Concerns about potential failure were due to the stiffness of hardened geopolymer cement mortar, and the possibility of the geopolymer mortar being incompatible with the existing asphalt surrounding the defect. However, after 2000 wheel passes, no surface defects were noticed (Figure 7). The visual assessment focused on surface cracking, delamination, de-bonding of the geopolymer from the asphalt, and material loss. The only indication of wear was some shining of the material surface. The skid resistance was measured before and after the accelerated wearing of the sample. The skid resistance decreased slightly from 43 to 41 after wearing. While this was a positive initial test, the performance falls short of the requirements set out by RRL Road Note 27 [15]. The minimum skid resistance value for materials used on public roads is 45, with trunk roads and motorways requiring 55, and bends and roundabouts requiring 65. Therefore, further work involving surface texturing will be required to develop a geopolymer mortar which is suitable of road pavement use. Also, it is suggested that samples should be subjected to 100,000 ± 1000 wheel passes [14]. While initial durability results appear positive, a more extensive testing programme will be required to determine the performance of the repair material after much greater exposure to wearing conditions.

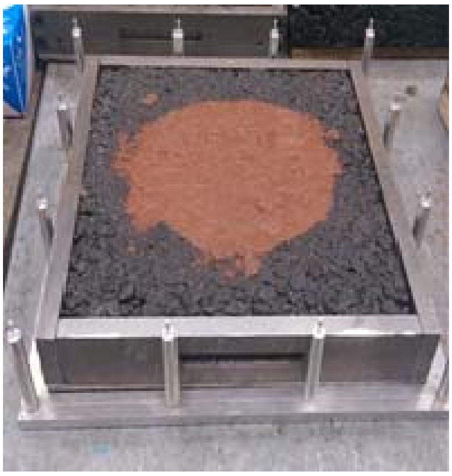

Figure 7. Geopolymer pothole repair material after simulated wearing.

3.4 High Friction Surfacing

The high friction surface slabs were subjected to 20,000 wheel passes, with texture depth and skid resistance measured prior to testing, and at various intervals during testing. Prior to testing, the texture depth of the geopolymer aggregate sample was recorded as 2.43 mm, with a skid resistance value of 80. The control slab had an initial texture depth of 2.58 mm, and a skid resistance value of 94. Figure 8 shows the changes in texture depth during testing. Figure 9 shows the changes in skid resistance during testing. After 20,000 wheel passes, the geopolymer slab retained a texture depth of 1.3 mm, and a skid resistance value of 55. This represented a 47% decrease in texture depth and a 31% decrease in skid resistance. This is compared with the calcined bauxite, which has a retained texture depth of 1.55 mm (40% texture loss) and a skid resistance value of 74 (21% skid resistance loss). Both slabs showed a significant decrease in texture depth after 1000 wheel passes. The geopolymer aggregate texture depth reduced by 39% after 1000 wheel passes, and the calcined bauxite texture depth reduced by 33%. After the initial 1000 wheel passes, the texture depth loss of the samples was more stable. While the retained texture depth of the geopolymer aggregate slab was significantly lower than the initial value, the 1.3 mm texture depth exceeds the minimum requirements for a road surface. The reference slab had a retained texture depth of 1.6 mm.

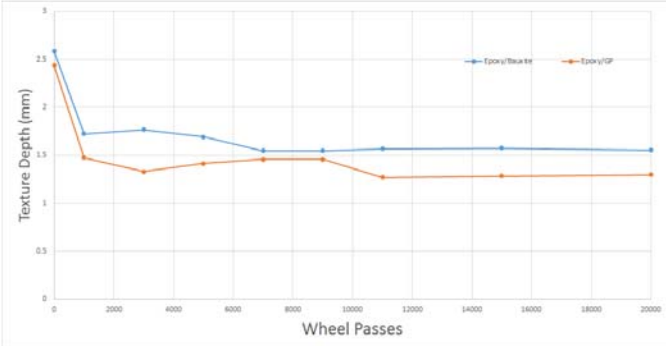

Figure 8. Effect of simulated wearing on surface texture depth.

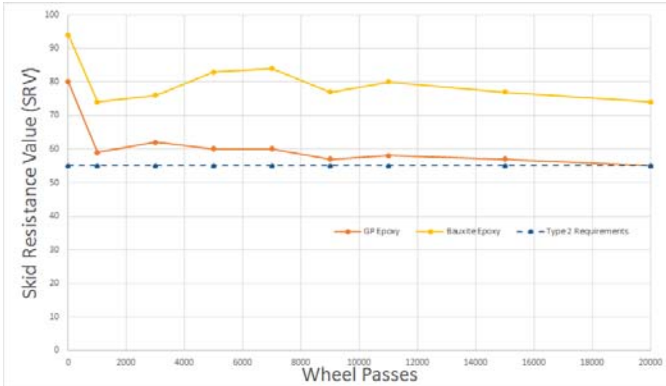

Figure 9. Effect of simulated wearing on skid resistance values.

The skid resistance value of the geopolymer aggregate slab can be classified as a Type 2 surface, according to RRL Road Note 27 [15], while the calcined bauxite slab achieved a Type 1 classification, as expected. This means that the geopolymer aggregate, without any further work or development, would be suitable for use in a type 2 application, such as trunk roads or motorways.

From the results, the skid resistance value differences between the samples may be attributed broadly to a difference in macrotexture depths. However, the results show that a decreasing texture depth doesn't directly compare with decreasing skid resistance values. This may suggest that factors other than macrotexture, such as aggregate shape and size may also have an effect of the skid resistance of a high friction surface. Also, some unexpected texture depth readings, such as the increase in geopolymer slab texture depth between 11,000 and 20,000 wheel passes, may be attributed to some aggregate being removed during testing. Further work is required in this area to better understand the factors which affect the skid resistance of high friction surfaces.

4 SUMMARY AND CONCLUSIONS

The first part of this investigation focused on the development of a geopolymer mortar mix design process, in order to produce a high strength geopolymer mortar. Mix designs were developed, based on the upper, middle and lower limits of content ranges which were considered for each variable in the mortar: powder, activator and water. Sand content was adjusted only to maintain a constant mix density. Compressive strengths at 7 days ranged from 54 to 69 N/mm^2, while at 28 days, compressive strengths ranged from 58 to 77 N/mm^2. Flexural strengths, as expected, were significantly lower with 28 day strengths ranging from 1.7 to 3.1 N/mm^2. Based on these results, mix 7, with a mean 28 day compressive strength of 76 N/mm^2 and flexural strength of 3.1 N/mm^2 was selected for workability tests and as a pothole repair material. The crushed geopolymer mortar specimens were then crushed, using a jaw crusher, to form an aggregate suitable for use as a high friction surface aggregate.

The second part of this study involved the application of a geopolymer cement-based material in two road pavement applications: a pothole repair material and a high friction surface aggregate. These initial results indicated the potential usefulness of geopolymer cement-based materials in highway applications. As a pothole repair material, no surface deformations were noticed, other than some minor shining of the geopolymer surface. However, texture depth and skid resistance values were below minimum requirements. Also, a longer test period with the road test machine is required to gain a better understanding of the geopolymer performance over time. As a high friction aggregate, the impressive results achieved at a very early stage in the research provide a strong starting point in the further development of a suitable alternative to calcined bauxite in a high friction surfacing system. The potential to recycle geopolymeric materials for this application may also prove to be a positive when considering the whole life cycle of geopolymer cement. Overall, geopolymer cement has been identified as a material which can be adapted to perform well in differing road surface applications.

This study has identified three main areas for further consideration in the research programme.

1. Further research into the potential use of geopolymer mortar pothole repairs, to improve setting times and with surface texturing applied to satisfy texture depth and skid resistance value requirements.
2. Optimisation of geopolymer strength to create a durable, high performance aggregate for use as a high friction aggregate.
3. Investigation into factors affecting high friction surfaces, using conventional measurement techniques and new 3D photogrammetry techniques. This is to be followed by further optimisation of the geopolymer aggregate in terms of strength, shape and size.

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